Probabilistic lower bounds on maximal determinants of binary matrices

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Abstract

Let $\mathcal{D}(n)$ be the maximal determinant for $n \times n$ $\{\pm 1\}$-matrices, and $\mathcal{R}(n) = \mathcal{D}(n)/n^{n/2}$ be the ratio of $\mathcal{D}(n)$ to the Hadamard upper bound. Using the probabilistic method, we prove new lower bounds on $\mathcal{D}(n)$ and $\mathcal{R}(n)$ in terms of $d = n - h$, where h is the order of a Hadamard matrix and h is maximal subject to $h \le n$. For example,

$$\mathcal{R}(n) > \left(\frac{2}{\pi e}\right)^{d/2} \quad \text{if } \ 1 \le d \le 3, \quad \text{and}$$

$$\mathcal{R}(n) > \left(\frac{2}{\pi e}\right)^{d/2} \left(1 - d^2\left(\frac{\pi}{2h}\right)^{1/2}\right) \quad \text{if } \ d > 3.$$

By a recent result of Livinskyi, $d^2/h^{1/2} \to 0$ as $n \to \infty$, so the second bound is close to $(\pi e/2)^{-d/2}$ for large n. Previous lower bounds tended to zero as $n \to \infty$ with d fixed, except in the cases $d \in \{0, 1\}$. For $d \ge 2$, our bounds are better for all sufficiently large n. If the Hadamard conjecture is true, then $d \le 3$, so the first bound above shows that $\mathcal{R}(n)$ is bounded below by a positive constant $(\pi e/2)^{-3/2} > 0.1133$.

1 Introduction

Let $\mathcal{D}(n)$ be the maximal determinant possible for an $n \times n$ matrix with elements in $\{\pm 1\}$. Hadamard [15] proved that $\mathcal{D}(n) \le n^{n/2}$, and the *Hadamard conjecture* is that a matrix achieving this upper bound exists for each positive integer n divisible by four. The function $\mathcal{R}(n) := \mathcal{D}(n)/n^{n/2}$ is a measure of the sharpness of the Hadamard bound. Clearly $\mathcal{R}(n) = 1$ if a Hadamard matrix of order n exists; otherwise $\mathcal{R}(n) < 1$. In this paper we give lower bounds on $\mathcal{D}(n)$ and $\mathcal{R}(n)$.

Let $\mathcal{H}$ be the set of orders of Hadamard matrices, and let $h \in \mathcal{H}$ be maximal subject to $h \le n$. Then $d = n - h$ can be regarded as the "gap" between n and the nearest (lower) Hadamard order. We are interested the case that n is not a Hadamard order, i.e. $d > 0$ and $\mathcal{R}(n) < 1$.

Except in the cases $d \in \{0, 1\}$, previous lower bounds on $\mathcal{R}(n)$ tended to zero as $n \to \infty$. For example, the well-known bound of Clements and Lindström [11, Corollary to Thm. 2] shows that $\mathcal{R}(n) > (3/4)^{n/2}$, and [5, Thm. 9] shows that $\mathcal{R}(n) \ge (ne/4)^{-d/2}$. In contrast, our results imply that, for fixed d, $\mathcal{R}(n)$ is bounded below by a positive constant (depending only on d).

Our lower bound proof uses the probabilistic method pioneered by Erdős (see for example [1, 13]). This method does not appear to have been applied previously to the Hadamard maximal determinant problem, except in the case $d = 1$ (so $n \equiv 1 \bmod 4$); in this case the concept of *excess* has been used [14], and lower bounds on the maximal excess were obtained by the probabilistic method [2, 9, 13, 14].

§2 describes our probabilistic construction and determines the mean μ and variance σ^2 of elements in the Schur complement generated by the construction (see Lemmas 2.6 and 2.9). Informally, we adjoin d extra columns to an $h \times h$ Hadamard matrix A, and fill their $h \times d$ entries with random (uniformly and independently distributed) ± 1 values. Then we adjoin d extra rows, and fill their $d \times (h+d)$ entries with values chosen deterministically in a way intended to approximately maximise the determinant of the final matrix $\widetilde{A}$. To do so, we use the fact that this determinant can be expressed in terms of the $d \times d$ Schur complement of A in $\widetilde{A}$.

In the case $d = 1$, this method is essentially the same as the known method involving the excess of matrices Hadamard-equivalent to A, and leads to the same bounds that can be obtained by bounding the excess in a probabilistic manner.

In §3 we give lower bound results on both $\mathcal{D}(n)$ and $\mathcal{R}(n)$. Of course, a lower bound on $\mathcal{D}(n)$ immediately gives an equivalent lower bound on $\mathcal{R}(n)$. However, we use some elementary inequalities to obtain simpler (though

slightly weaker) bounds on $\mathcal{R}(n)$. For example, if $d \le 3$ then Theorem 3.6 states that $\mathcal{D}(n) \ge h^{h/2}(\mu^d - \eta)$, where μ and η are certain functions of h and d. Theorem 3.6 also states the (weaker) result that $\mathcal{R}(n) > (\pi e/2)^{-d/2}$. The lower bound on $\mathcal{R}(n)$ clearly shows that the ratio of our bound to the Hadamard bound is at least $(\pi e/2)^{-3/2} > 0.1133$, whereas this conclusion is not immediately obvious from the lower bound on $\mathcal{D}(n)$.

We outline the bounds on $\mathcal{R}(n)$ here. Theorem 3.4 gives a lower bound

$$\mathcal{R}(n) > \left(\frac{2}{\pi e}\right)^{d/2} \left(1 - d^2 \left(\frac{\pi}{2h}\right)^{1/2}\right) \tag{1}$$

which is nontrivial whenever $h > \pi d^4/2$. By the results of Livinskyi [20], $d = O(h^{1/6})$ as $h \to \infty$ (see [7, §6] for details), so the condition $h > \pi d^4/2$ holds for all sufficiently large n. Also, as $n \to \infty$, $d^2/h^{1/2} = O(n^{-1/6}) \to 0$, so the lower bound (1) is close to $(\pi e/2)^{-d/2}$. For fixed $d > 1$ and large n, our lower bounds on $\mathcal{R}(n)$ are better than previous bounds (see Table 1 in §4).

Theorem 3.6 applies only for $d \le 3$, but whenever it is applicable it gives sharper results than Theorem 3.4. In fact, Theorem 3.6 shows that the factor $1 - O(d^2/h^{1/2})$ in (1) can be omitted when $d \le 3$, giving $\mathcal{R}(n) > (\pi e/2)^{-d/2}$. Theorem 3.6 is always applicable if the Hadamard conjecture is true, since this conjecture implies that $d \le 3$.

In §4, we give some numerical examples to illustrate Theorems 3.4 and 3.6, and to compare our results with previous bounds on $\mathcal{D}(n)$ and/or $\mathcal{R}(n)$.

Rokicki *et al* [23] showed, by extensive computation, that $\mathcal{R}(n) \ge 1/2$ for $n \le 120$, and conjectured that this inequality always holds. It seems difficult to bridge the gap between the constants $1/2$ and $(\pi e/2)^{-3/2}$ by the probabilistic method. The best that we can do is to improve the term of order $d^2/h^{1/2}$ in the bound (1) at the expense of a more complicated proof – for details see [7].

2 The probabilistic construction

We now describe our probabilistic construction and prove some of its properties. In the case $d = 1$ our construction reduces to that of Best [2].

Let A be a Hadamard matrix of order $h \ge 4$. We add a border of d rows and columns to give a larger (square) matrix $\widetilde{A}$ of order n. The border is defined by matrices B, C and D as shown:

$$\widetilde{A} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} . \tag{2}$$

The $d \times d$ matrix $D - CA^{-1}B$ is known as the *Schur complement* of A in $\widetilde{A}$ after Schur [24]. The *Schur complement lemma* (see for example [12]) gives

$$\det(\widetilde{A}) = \det(A)\det(D - CA^{-1}B). \tag{3}$$

In our construction the matrices A, B, and C have entries in $\{\pm 1\}$. We allow the matrix D to have entries in $\{0, \pm 1\}$, but each zero entry can be replaced by one of $+1$ or -1 without decreasing $|\det(\widetilde{A})|$, so any lower bounds that we obtain on $\max(|\det(\widetilde{A})|)$ are valid lower bounds on maximal determinants of $n \times n$ $\{\pm 1\}$-matrices. Note that the Schur complement is not in general a $\{\pm 1\}$-matrix.

In the proof of Lemma 3.2 we show that our choice of B, C and D gives a Schur complement $D - CA^{-1}B$ that, with positive probability, has sufficiently large determinant. From equation (3) and the fact that A is a Hadamard matrix, a large value of $\det(D - CA^{-1}B)$ implies a large value of $\det(\widetilde{A})$.

2.1 Details of the probabilistic construction

Let A be any Hadamard matrix of order h. B is allowed to range over the set of all $h \times d$ $\{\pm 1\}$-matrices, chosen uniformly and independently from the 2^{hd} possibilities. The $d \times h$ matrix $C = (c_{ij})$ is a function of B. We choose

$$c_{ij} = \operatorname{sgn}(A^T B)_{ji}\,,$$

where

$$\operatorname{sgn}(x) := \begin{cases} +1 \text{ if } x \geq 0, \\ -1 \text{ if } x < 0. \end{cases}$$

To complete the construction, we choose $D = -I$. As mentioned above, it is inconsequential that D is not a $\{\pm 1\}$-matrix.

2.2 Properties of the construction

Define $F = CA^{-1}B$ and $G = F - D = F + I$ (so $-G$ is the Schur complement defined above). Note that, since A is a Hadamard matrix, $A^T = hA^{-1}$, so $hF = CA^TB$.

Since B is random, we expect the elements of A^TB to be usually of order $h^{1/2}$. The definition of C ensures that there is no cancellation in the inner products defining the diagonal entries of $hF = C \cdot (A^TB)$. Thus, we expect the diagonal entries f_{ii} of F to be nonnegative and of order $h^{1/2}$, but the off-diagonal entries f_{ij} $(i \neq j)$ to be of order unity with high probability.

Similarly for the elements of G. This intuition is justified by Lemmas 2.6 and 2.9.

In the following we denote the expectation of a random variable X by $\mathbb{E}[X]$, and the variance by $\mathbb{V}[X] = \mathbb{E}[X^2] - \mathbb{E}[X]^2$.

Lemmas 2.1–2.2 are essentially due to Best [2] and Lindsey.[1]

Lemma 2.1. *If $h \geq 2$ and $F = (f_{ij})$ is chosen as above, then*

$$\mathbb{E}[f_{ij}] = \begin{cases} 2^{-h} h \binom{h}{h/2} & \textit{if } \ i = j, \\ 0 \ \ \textit{if } \ i \neq j. \end{cases}$$

Proof. The case $i = j$ follows as in Best [2, proof of Theorem 3]. The case $i \neq j$ is easy, since B is chosen randomly. □

Lemma 2.2. *If $F = (f_{ij})$ is chosen as above, then $|f_{ij}| \leq h^{1/2}$ for $1 \leq i, j \leq d$.*

Proof. The matrix $Q := h^{-1/2} A^T$ is orthogonal with rows and columns of unit length (in the Euclidean norm). Thus $||Qb||_2 = ||b||_2 = h^{1/2}$ for each column b of B. Since $h^{1/2} F = C.QB$, each element $h^{1/2} f_{ij}$ of $h^{1/2} F$ is the inner product of a row of C (having length $h^{1/2}$) and a column of QB (also having length $h^{1/2}$). It follows from the Cauchy-Schwartz inequality that $|h^{1/2} f_{ij}| \leq h^{1/2} \cdot h^{1/2} = h$, so $|f_{ij}| \leq h^{1/2}$. □

Lemma 2.3. *If F is chosen as above and $\{i, j\} \cap \{k, \ell\} = \emptyset$, then f_{ij} and $f_{k\ell}$ are independent.*

Proof. This follows from the fact that f_{ij} depends only on the fixed matrix A and on columns i and j of B. □

Lemma 2.4. *Let $A \in \{\pm 1\}^{h \times h}$ be a Hadamard matrix, $C \in \{\pm 1\}^{d \times h}$, and $U = CA^{-1}$. Then, for each i with $1 \leq i \leq d$,*

$$\sum_{j=1}^{h} u_{ij}^2 = 1.$$

Proof. Since A is Hadamard, $UU^T = h^{-1} CC^T$. Also, since $c_{ij} = \pm 1$, $\operatorname{diag}(CC^T) = hI$. Thus $\operatorname{diag}(UU^T) = I$. □

Lemma 2.5. *If $F = (f_{ij})$ is chosen as above, then*

$$\mathbb{E}[f_{ij}^2] = 1 \ \textit{for} \ \ i \neq j. \tag{4}$$

[1] See [13, footnote on pg. 88].

Proof. We can assume, without loss of generality, that $i = 1$, $j > 1$. Write $F = UB$, where $U = CA^{-1} = h^{-1}CA^T$. Now

$$f_{1j} = \sum_k u_{1k} b_{kj}, \tag{5}$$

where

$$u_{1k} = \frac{1}{h} \sum_\ell c_{1\ell} a_{k\ell}, \quad c_{1\ell} = \operatorname{sgn}\left(\sum_m b_{m1} a_{m\ell}\right).$$

Observe that $c_{1\ell}$ and u_{1k} depend only on the first column of B. Thus, f_{1j} depends only on the first and j-th columns of B. If we fix the first column of B and take expectations over all choices of the other columns, we obtain

$$\mathbb{E}[f_{1j}^2] = \mathbb{E}\left[\sum_k \sum_\ell u_{1k} u_{1\ell} b_{kj} b_{\ell j}\right].$$

The expectation of the terms with $k \neq \ell$ vanishes, and the expectation of the terms with $k = \ell$ is $\sum_k u_{1k}^2$. Thus, (4) follows from Lemma 2.4. $\square$

Lemma 2.6. *Let A be a Hadamard matrix of order $h \geq 4$ and B, C be $\{\pm 1\}$-matrices chosen as above. Let $G = F + I$ where $F = CA^{-1}B$. Then*

$$\begin{aligned}
\mathbb{E}[g_{ii}] &= 1 + \frac{h}{2^h}\binom{h}{h/2}, && (6)\\
\mathbb{E}[g_{ij}] &= 0 \textit{ for } 1 \leq i, j \leq d,\ i \neq j, && (7)\\
\mathbb{V}[g_{ii}] &= 1 + \frac{h(h-1)}{2^{h+1}}\binom{h/2}{h/4}^2 - \frac{h^2}{2^{2h}}\binom{h}{h/2}^2, && (8)\\
\mathbb{V}[g_{ij}] &= 1 \textit{ for } 1 \leq i, j \leq d,\ i \neq j. && (9)
\end{aligned}$$

Proof. Since $G = F + I$, the results (6), (7) and (9) follow from Lemma 2.1 and Lemma 2.5 above. Thus, we only need to prove (8). Since $g_{ii} = f_{ii} + 1$, it is sufficient to compute $\mathbb{V}[f_{ii}]$.

Since A is a Hadamard matrix, $hF = CA^TB$. We compute the second moment about the origin of the diagonal elements hf_{ii} of hF. Since h is a Hadamard order and $h \geq 4$, we can write $h = 4k$ where $k \in \mathbb{Z}$. Consider h independent random variables $X_j \in \{\pm 1\}$, $1 \leq j \leq h$, where $X_j = +1$ with probability $1/2$. Define random variables S_1, S_2 by

$$S_1 = \sum_{j=1}^{4k} X_j, \quad S_2 = \sum_{j=1}^{2k} X_j - \sum_{j=2k+1}^{4k} X_j\,.$$

Consider a particular choice of $X_1, \dots, X_h$ and suppose that $k + p$ of $X_1, \dots, X_{2k}$ are $+1$, and that $k+q$ of $X_{2k+1}, \dots, X_{4k}$ are $+1$. Then we have $S_1 = 2(p+q)$ and $S_2 = 2(p-q)$. Thus, taking expectations over all 2^{4k} possible (equally likely) choices, we see that

$$\begin{aligned}\mathbb{E}[|S_1 S_2|] = 4\mathbb{E}[|p^2 - q^2|] &= \frac{4}{2^{4k}} \sum_p \sum_q \binom{2k}{k+p}\binom{2k}{k+q} |p^2 - q^2| \\ &= \frac{4}{2^{4k}} \cdot 2k^2 \binom{2k}{k}^2 = \frac{h^2}{2^{h+1}} \binom{2k}{k}^2 .\end{aligned}$$

Here the closed form for the double sum is a special case of [4, Prop. 1.1]. By the definitions of B, C and F, we see that hf_{ii} is a sum of the form $Y_1 + Y_2 + \cdots + Y_h$, where each Y_j is a random variable with the same distribution as $|S_1|$, and each product $Y_j Y_\ell$ (for $j \neq \ell$) has the same distribution as $|S_1 S_2|$. Also, Y_j^2 has the same distribution as $|S_1|^2 = S_1^2$. The random variables Y_j are not independent, but by linearity of expectations we obtain

$$h^2 \mathbb{E}[f_{ii}^2] = h\mathbb{E}[S_1^2] + h(h-1)\mathbb{E}[|S_1 S_2|] = h^2 + h(h-1) \cdot \frac{h^2}{2^{h+1}} \binom{2k}{k}^2 .$$

This gives

$$\mathbb{E}[f_{ii}^2] = 1 + \frac{h(h-1)}{2^{h+1}} \binom{2k}{k}^2 .$$

The result for $\mathbb{V}[g_{ii}]$ now follows from $\mathbb{V}[g_{ii}] = \mathbb{V}[f_{ii}] = \mathbb{E}[f_{ii}^2] - \mathbb{E}[f_{ii}]^2$. □

For convenience we write $\mu(h) := \mathbb{E}[g_{ii}] = \mathbb{E}[f_{ii}] + 1$ and $\sigma(h)^2 := \mathbb{V}[g_{ii}]$. If h is understood from the context we write simply μ and σ^2 respectively.

To estimate μ and σ^2 from Lemma 2.6, we need a sufficiently accurate estimate for a central binomial coefficient $\binom{2m}{m}$ (where $m = h/2$ or $h/4$). An asymptotic expansion for $\ln \binom{2m}{m}$ may be deduced from Stirling's asymptotic expansion of $\ln \Gamma(z)$, as in [16]. However, [16] does not give an error bound. We state such a bound in the following Lemma.

Lemma 2.7. *If k and m are positive integers, then*

$$\ln \binom{2m}{m} = m \ln 4 - \frac{\ln(\pi m)}{2} - \sum_{j=1}^{k-1} \frac{B_{2j}(1 - 4^{-j})}{j(2j-1)} m^{1-2j} + e_k(m), \tag{10}$$

where

$$|e_k(m)| < \frac{|B_{2k}|}{k(2k-1)} m^{1-2k}. \tag{11}$$

Proof. Using the facts that m is real and positive, and that the sign of the Bernoulli number B_{2k} is $(-1)^{k-1}$, we obtain from Olver [21, (4.03) and (4.05) of Ch. 8] that

$$\ln\Gamma(m) = (m-\tfrac{1}{2})\ln m - m + \frac{\ln(2\pi)}{2} + \sum_{j=1}^{k-1} \frac{B_{2j}}{2j(2j-1)} m^{1-2j} - (-1)^k r_k(m), \tag{12}$$

where

$$0 < r_k(m) < \frac{|B_{2k}|}{2k(2k-1)} m^{1-2k}. \tag{13}$$

Now

$$\binom{2m}{m} = \frac{(2m)!}{m!m!} = \frac{2}{m}\frac{\Gamma(2m)}{\Gamma(m)^2},$$

so from (12) and the same equation with $m \mapsto 2m$ we obtain (10) with

$$e_k(m) = (-1)^k(2r_k(m) - r_k(2m)).$$

Using the bound (13), this gives

$$e_k(m) = \frac{(-1)^k|B_{2k}|}{k(2k-1)} m^{1-2k}\theta,$$

where $-2^{-2k} < \theta < 1$. In particular, $|\theta| < 1$, so we obtain the desired bound (11). $\square$

Remark 2.8. Lemma 2.7 can be sharpened. In fact, $e_k(m)$ has the same sign as the first omitted term (corresponding to $j = k$) and has smaller magnitude. This is proved in [3, Corollary 2].

We now show that $\mu(h)$ is of order $h^{1/2}$, and that $\sigma(h)$ is bounded.

Lemma 2.9. *For $h \in 4\mathbb{Z}$, $h \ge 4$, we have*

$$\sigma(h)^2 < 1 \tag{14}$$

and

$$\sqrt{\frac{2h}{\pi}} + 0.9 < \mu(h) < \sqrt{\frac{2h}{\pi}} + 1. \tag{15}$$

Proof. From Lemma 2.7 with $k = 2$ and m a positive integer, we have

$$\binom{2m}{m} = \frac{4^m}{\sqrt{\pi m}} \exp\left[-\frac{1}{8m} + \frac{\theta_m}{180m^3}\right], \tag{16}$$

where $|\theta_m| < 1$.

First consider the bounds (16) on $\mu(h)$. Taking $m = h/2$ and using the expression (6) for $\mu(h)$, the inequality (15) is equivalent to

$$\sqrt{\frac{m}{\pi}} - \frac{1}{20} < \frac{m}{4^m}\binom{2m}{m} < \sqrt{\frac{m}{\pi}}\,.$$

The upper bound is immediate from (16), since $-\frac{1}{8m} + \frac{1}{180m^3} < 0$.

For the lower bound, a computation verifies the inequality for $m = 2$, since $\sqrt{2/\pi} - \frac{1}{20} < \frac{3}{4} = \frac{m}{4^m}\binom{2m}{m}$. Hence, we can assume that $m \ge 4$. The lower bound now follows from (16), since

$$\frac{m}{4^m}\binom{2m}{m} > \sqrt{\frac{m}{\pi}}\,\exp\left[-\frac{1}{8m} - \frac{1}{180m^3}\right] > \sqrt{\frac{m}{\pi}}\,\left[1 - \frac{1}{8m} - \frac{1}{180m^3}\right]$$

and

$$\sqrt{\frac{m}{\pi}}\left[\frac{1}{8m} + \frac{1}{180m^3}\right] < \frac{1}{20}\,.$$

Now consider the upper bound (14) on $\sigma(h)^2$. From (16) we have

$$\binom{h/2}{h/4}^2 < \frac{2^{h+2}}{\pi h}\exp\left[-\frac{1}{h} + \frac{32}{45h^3}\right]$$

and

$$\binom{h}{h/2}^2 > \frac{2^{2h+1}}{\pi h}\exp\left[-\frac{1}{2h} - \frac{4}{45h^3}\right]\,.$$

Using these inequalities in (8) and simplifying gives

$$\begin{aligned}\sigma(h)^2 < 1 + \frac{2h}{\pi}&\left[\exp\left(-\frac{1}{h} + \frac{32}{45h^3}\right) - \exp\left(-\frac{1}{2h} - \frac{4}{45h^3}\right)\right]\\ &- \frac{2}{\pi}\exp\left(-\frac{1}{h} + \frac{32}{45h^3}\right)\,.\end{aligned} \tag{17}$$

It is easy to see that the term in square brackets is negative for $h \ge 4$, so (17) implies (14). □

Remark 2.10. *We can show from* (17) *and a corresponding lower bound on* $\sigma(h)^2$ *that* $\sigma(h+4)^2 < \sigma(h)^2$, *so* $\sigma(h)^2$ *is monotonic decreasing and bounded above by* $\sigma(4)^2 = \frac{1}{4}$. *Also, for large* h *we have* $\sigma(h)^2 = (1 - 3/\pi) + O(1/h)$. *Since these results are not needed below, we omit the details.*

3 A probabilistic lower bound

We now prove lower bounds on $\mathcal{D}(n)$ and $\mathcal{R}(n)$ where, as usual, $n = h + d$ and h is the order of a Hadamard matrix. The key result is Lemma 3.2. Theorem 3.4 simply converts the result of Lemma 3.2 into lower bounds on $\mathcal{D}(n)$ and $\mathcal{R}(n)$, giving away a little for the sake of simplicity in the latter case.

For the proof of Lemma 3.2 we need the following bound on the determinant of a matrix which is "close" to the identity matrix. It is due to Ostrowski [22, eqn. (5,5)]; see also [8, Corollary 1].

Lemma 3.1 (Ostrowski). *If $M = I - E \in \mathbb{R}^{d\times d}$, $|e_{ij}| \le \varepsilon$ for $1 \le i, j \le d$, and $d\varepsilon \le 1$, then*

$$\det(M) \ge 1 - d\varepsilon.$$

The idea of Lemma 3.2 is that we can, with positive probability, apply Lemma 3.1 to the matrix $M = \mu^{-1}G$, thus obtaining a lower bound on the maximum value attained by $\det(G)$.

Lemma 3.2. *Suppose $d \ge 1$, $4 \le h \in \mathcal{H}$, $n = h + d$, G as in §2.2. Then, with positive probability,*

$$\frac{\det G}{\mu^d} \ge 1 - \frac{d^2}{\mu}. \tag{18}$$

Proof. Let λ be a positive parameter to be chosen later, and $\mu = \mu(h)$. We say that G is *good* if the conditions of Lemma 3.1 apply with $M = \mu^{-1}G$ and $\varepsilon = \lambda/\mu$. Otherwise G is *bad*.

Assume $1 \le i, j \le d$. From Lemma 2.6, $\mathbb{V}[g_{ij}] = 1$ for $i \ne j$; from Lemma 2.9, $\mathbb{V}[g_{ii}] = \sigma^2 < 1$. It follows from Chebyshev's inequality [10] that

$$\mathbb{P}[|g_{ij}| \ge \lambda] \le \frac{1}{\lambda^2} \ \text{ for } \ i \ne j,$$

and

$$\mathbb{P}[|g_{ii} - \mu| \ge \lambda] \le \frac{\sigma^2}{\lambda^2}.$$

Thus,

$$\mathbb{P}[G \text{ is bad}] \le \frac{d(d-1)}{\lambda^2} + \frac{d\sigma^2}{\lambda^2} < \frac{d^2}{\lambda^2}.$$

Taking $\lambda = d$ gives $\mathbb{P}[G \text{ is bad}] < 1$, so $\mathbb{P}[G \text{ is good}]$ is positive. Whenever G is good we can apply Lemma 3.1 to $\mu^{-1}G$, obtaining $\mu^{-d}\det(G) = \det(\mu^{-1}G) \ge 1 - d\varepsilon = 1 - d\lambda/\mu = 1 - d^2/\mu$. ∎

The following lemma is useful for deducing lower bounds on $\mathcal{R}(n)$.

Lemma 3.3. *If $n = h + d > h > 0$, then*

$$(h/n)^n > \exp(-d - d^2/h).$$

Proof. Writing $x = d/n$, the inequality $\ln(1-x) > -x/(1-x)$ implies that

$$(1-x)^n \; > \; \exp\left(-\frac{nx}{1-x}\right).$$

Since $1 - x = h/n$, we obtain

$$\left(\frac{h}{n}\right)^n \; > \; \exp\left(\frac{-d}{1-d/n}\right) = \exp(-d - d^2/h). \qquad \square$$

We are now ready to prove our main result. Theorem 3.4 gives lower bounds on $\mathcal{D}(n)$ and $\mathcal{R}(n)$. If the reader needs a lower bound for a specific value of n, then the inequality (19) should be used. The inequality (20) is slightly weaker than what can be obtained simply by dividing both sides of (19) by $n^{n/2}$, but it shows more clearly the asymptotic behaviour if n and h are large but d is small.

Theorem 3.4. *Suppose $d \geq 1$, $4 \leq h \in \mathcal{H}$, and $n = h + d$. Then*

$$\mathcal{D}(n) \geq h^{h/2}\mu^d(1 - d^2/\mu), \tag{19}$$

where $\mu = 1 + \frac{h}{2^h}\binom{h}{h/2}$. Also,

$$\mathcal{R}(n) > \left(\frac{2}{\pi e}\right)^{d/2}\left(1 - d^2\sqrt{\frac{\pi}{2h}}\right). \tag{20}$$

Proof. Lemma 3.2 and the Schur complement lemma imply that there exists an $n \times n$ $\{\pm 1\}$-matrix with determinant at least $h^{h/2}\mu^d(1 - d^2/\mu)$. Thus, (19) follows from the definition of $\mathcal{D}(n)$.

We now show that (20) follows from (19) by some elementary inequalities. Write $c := \sqrt{2/\pi}$. We can assume that $d^2 < ch^{1/2}$, for there is nothing to prove unless the right side of (20) is positive. From Lemma 2.9, $ch^{1/2} < \mu$, so $d^2 < \mu$. Also, from (19),

$$\mathcal{R}(n) \geq \frac{h^{h/2}\mu^d}{n^{n/2}}\left(1 - \frac{d^2}{\mu}\right). \tag{21}$$

Using $ch^{1/2} < \mu$, this gives

$$\mathcal{R}(n) > c^d(h/n)^{n/2}(1 - d^2/\mu).$$

By Lemma 3.3, $(h/n)^n > \exp(-d - d^2/h)$, so

$$\mathcal{R}(n) > c^d e^{-d/2} f = \left(\frac{2}{\pi e}\right)^{d/2} f, \tag{22}$$

where

$$f = \exp\left(-\frac{d^2}{2h}\right)\left(1 - \frac{d^2}{\mu}\right). \tag{23}$$

Thus, to prove (20), it suffices to prove that $f \ge 1 - d^2/(ch^{1/2})$. Since $\exp(-d^2/(2h)) \ge 1 - d^2/(2h)$, it suffices to prove that

$$\left(1 - \frac{d^2}{2h}\right)\left(1 - \frac{d^2}{\mu}\right) \ge 1 - \frac{d^2}{ch^{1/2}} \cdot \tag{24}$$

Expanding and simplifying shows that the inequality (24) is equivalent to

$$2h + \mu \le d^2 + \mu\sqrt{2\pi h}. \tag{25}$$

Now, by Lemma 2.9, $\mu > c\sqrt{h} + 0.9$, so $\mu\sqrt{2\pi h} > 2h + 0.9\sqrt{2\pi h}$ (using $c\sqrt{2\pi} = 2$). Thus, to prove (25), it suffices to show that $\mu \le d^2 + 0.9\sqrt{2\pi h}$. Using Lemma 2.9 again, we have $\mu \le ch^{1/2} + 1$, so it suffices to show that

$$ch^{1/2} + 1 \le 0.9\sqrt{2\pi h} + d^2.$$

This follows from $c \le 0.9\sqrt{2\pi}$ and $1 \le d^2$, so the proof is complete. □

Remark 3.5. The inequality (20) of Theorem 3.4 gives a nontrivial lower bound on $\mathcal{R}(n)$ iff the second factor in the bound is positive, i.e. iff $h > \pi d^4/2$. By Livinskyi's results [20], this condition holds for all sufficiently large n (assuming as always that we choose the maximal $h \le n$ for given n).

The Hadamard conjecture implies that $d \le 3$. Theorem 3.6 improves on Theorem 3.4 under the assumption that $d \le 3$. The proof of Theorem 3.6 is conceptually simpler than that of Theorem 3.4, since it does not require any bounds on the variance $\sigma(h)^2$. In the proof of Theorem 3.6 we simply expand $\det(G)$, obtaining $d!$ terms. By Lemma 2.3, the expectation of the diagonal term is $\mathbb{E}[g_{11} \cdots g_{dd}] = \mu^d$. The expectation of the off-diagonal terms can be bounded to give the desired lower bound on $\mathcal{D}(n)$. The same approach gives weak results for $d > 3$ because of the large number $(d! - 1)$ of off-diagonal terms (see [6, Theorem 1]).

Theorem 3.6. *If $1 \le d \le 3$, $h \in \mathcal{H}$, $n = h + d$, and μ as in* (19)*, then*

$$\mathcal{D}(n) \ge h^{h/2}(\mu^d - \eta) \ \ \text{and} \ \ \mathcal{R}(n) > \left(\frac{2}{\pi e}\right)^{d/2},$$

where

$$\eta = \begin{cases} d - 1 \ \text{if } 1 \le d \le 2, \\ 5h^{1/2} + 3 \ \text{if } d = 3. \end{cases}$$

Proof. It is easy to verify the result for $h \in \{1, 2\}$, so suppose that $h \ge 4$. For notational convenience we give the proof for the case $d = 2$. The cases $d \in \{1, 3\}$ are similar.[2]

Since $G = F + I$, we have $g_{ii} = f_{ii} + 1$ and $\det(G) = g_{11}g_{22} - f_{12}f_{21}$. By Lemma 2.3, the diagonal elements g_{11} and g_{22} are independent, so

$$\mathbb{E}[g_{11}g_{22}] = \mathbb{E}[g_{11}]\mathbb{E}[g_{22}] = \mu^2.$$

By the Cauchy-Schwarz inequality and Lemma 2.5,

$$\mathbb{E}[f_{12}f_{21}]^2 \le \mathbb{E}[f_{12}^2]\mathbb{E}[f_{21}^2] = 1.$$

Thus

$$\mathbb{E}[\det(G)] = \mathbb{E}[g_{11}g_{22}] - \mathbb{E}[f_{12}f_{21}] \ge \mu^2 - 1.$$

There must exist some G_0 with $\det(G_0) \ge \mathbb{E}[\det(G)] \ge \mu^2 - 1$; hence

$$\mathcal{D}(n) \ge h^{h/2}(\mu^2 - 1).$$

This proves the required lower bound for $\mathcal{D}(n)$ if $d = 2$. We now deduce the required lower bound for $\mathcal{R}(n) = \mathcal{D}(n)/n^{n/2}$. Define $c := \sqrt{2/\pi}$ and $K := 0.9/c$. From Lemma 2.9, $\mu \ge c(h^{1/2} + K)$, so $\mu^2 \ge c^2h(1 + 2Kh^{-1/2})$. Thus, using $n = h + 2$,

$$\mathcal{D}(n) \ge c^2h^{n/2}\left(1 + 2Kh^{-1/2} - \frac{\eta}{c^2h}\right).$$

From Lemma 3.3 with $d = 2$, $(h/n)^{n/2} \ge e^{-1-2/h} \ge e^{-1}(1 - 2/h)$, so

$$\mathcal{R}(n) = \frac{\mathcal{D}(n)}{n^{n/2}} \ge \left(\frac{2}{\pi e}\right)\left(1 + 2Kh^{-1/2} - \frac{1}{c^2h}\right)\left(1 - \frac{2}{h}\right).$$

Since K is positive, the term $2Kh^{-1/2}$ dominates the $O(h^{-1})$ terms, and the result $\mathcal{R}(n) > 2/(\pi e)$ follows for all sufficiently large h. In fact, a small computation shows that the inequality holds for all $h \ge 4$. $\square$

[2] A detailed proof for the case $d = 3$ is given in [7, proof of Lemma 17].

4 Numerical examples

In this section we give some numerical comparisons between our lower bounds and previously-known bounds.

There are two well-known approaches to constructing a large-determinant $\{\pm 1\}$-matrix of order n. The *bordering* approach takes a Hadamard matrix H of order $h \le n$ and adjoins a border of $d = n - h$ rows and columns. The border is constructed in a manner intended to result in a large determinant. Previously, deterministic constructions were used – see for example [5, Lemma 7]. In this paper we have used a probabilistic construction.

The *minors* approach takes a Hadamard matrix H_+ of order $h_+ \ge n$ and finds an $n \times n$ submatrix with large determinant. This approach was used deterministically by Koukouvinos *et al* [17, 18], and probabilistically by de Launey and Levin [19]. The deterministic approach can be generalised using a theorem of Szöllősi [25], and this is better for $h_+ \le n + 6$ than the probabilistic approach of [19] – see [5, Remarks 6 and 22].

To illustrate Theorem 3.4, consider the case $n = 668$, $d = 4$. At the time of writing, n is the smallest positive multiple of 4 that is not known to be in $\mathcal{H}$. It is known that $h := n - 4 \in \mathcal{H}$ and $h_+ := n + 4 \in \mathcal{H}$.
The deterministic bordering approach [5, Lemma 7] gives a lower bound $\mathcal{R}(n) \ge 2^d h^{h/2}/n^{n/2} \approx 4.88 \times 10^{-6}$. The deterministic minors approach gives a lower bound $\mathcal{R}(n) \ge 16 h_+^{h_+/2-4}/n^{n/2} \approx 2.60 \times 10^{-4}$. The probabilistic bordering approach of Theorem 3.4 gives a lower bound (eqn. (21) above) $\mathcal{R}(n) \ge h^{h/2}\mu^d(1 - d^2/\mu)/n^{n/2} \approx 1.69 \times 10^{-2}$, where μ is as in (19). For comparison, our conjectured lower bound is $(\pi e/2)^{-d/2} \approx 5.48 \times 10^{-2}$.

Table 1: Asymptotics of lower bounds on $\mathcal{R}(n)$ as $n \to \infty$.

d	KMS [17]	B&O [5]	Theorem 3.6
1	$4\left(\frac{e}{n}\right)^{3/2} \approx \frac{17.93}{n^{3/2}}$	$\left(\frac{2}{\pi e}\right)^{1/2} \approx 0.4839$	$\left(\frac{2}{\pi e}\right)^{1/2} \approx 0.4839$
2	$\frac{2e}{n} \approx \frac{5.437}{n}$	$\left(\frac{8}{\pi e^2 n}\right)^{1/2} \approx \frac{0.5871}{n^{1/2}}$	$\frac{2}{\pi e} \approx 0.2342$
3	$\left(\frac{e}{n}\right)^{1/2} \approx \frac{1.649}{n^{1/2}}$	$\left(\frac{e}{n}\right)^{1/2} \approx \frac{1.649}{n^{1/2}}$	$\left(\frac{2}{\pi e}\right)^{3/2} \approx 0.1133$

To illustrate Theorem 3.6, Table 1 summarises the asymptotics of some lower bounds on $\mathcal{R}(n)$ for $d = (n \bmod 4) \in \{1, 2, 3\}$, assuming that $n-d \in \mathcal{H}$, $n+4-d \in \mathcal{H}$. The bounds are those given in Koukouvinos *et al* [17], Brent and Osborn [5, Table 1], and Theorem 3.6 of the present paper. It can be seen that we improve on the previous bounds by a factor of order at least $n^{1/2}$ for $d \in \{2, 3\}$.

Since asymptotics may be misleading for small n, Table 2 gives lower bounds on $\mathcal{R}(n)$ for various values of $n \equiv 2 \bmod 4$ (so $d = 2$).

Table 2: Comparison of lower bounds on $\mathcal{R}(n)$ for $d = 2$.

n	KMS [17]	B&O [5]	Thm. 3.4	Thm. 3.6
10	0.4147	0.1856	–	0.3752
14	0.3183	0.1569	–	0.3609
18	0.2581	0.1384	0.0127	0.3498
98	0.0538	0.0593	0.1601	0.2897
998	0.0054	0.0186	0.2142	0.2524
limit	0.0000	0.0000	0.2342	0.2342

In the case $d = 3$, a computation shows that the first bound of our Theorem 3.6 is sharper than the bound $\mathcal{D}(n) \geq (n+1)^{(n-1)/2}$ of [17, Thm. 2] if $n \geq 135$ (where the latter bound assumes that $n + 1 \in \mathcal{H}$).

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References

[1] N. Alon and J. H. Spencer, *The Probabilistic Method*, 3rd edn., Wiley, 2008.

[2] M. R. Best, The excess of a Hadamard matrix, *Nederl. Akad. Wetensch. Proc. Ser. A* **80** = *Indag. Math.* **39** (1977), 357–361.

[3] R. P. Brent, *Asymptotic approximation of central binomial coefficients with rigorous error bounds*, arXiv:1608.04834v1, 17 August 2016, 11 pp.

[4] R. P. Brent, C. Krattenthaler and S. O. Warnaar, Discrete analogues of Mehta-type integrals, *J. Combin. Theory Ser. A* **144** (2016), 80–138. `http://dx.doi.org/10.1016/j.jcta.2016.06.005`.

[5] R. P. Brent and J. H. Osborn, General lower bounds on maximal determinants of binary matrices, *Electron. J. Comb.* **20**(2), 2013, #P15, 12 pp.

[6] R. P. Brent, J. H. Osborn and W. D. Smith, *Lower bounds on maximal determinants of* ± 1 *matrices via the probabilistic method*, arXiv:1211.3248v3, 5 May 2013, 32 pp.

[7] R. P. Brent, J. H. Osborn and W. D. Smith, *Lower bounds on maximal determinants of binary matrices via the probabilistic method*, arXiv:1402.6817v2, 13 March 2014, 37 pp.

[8] R. P. Brent, J. H. Osborn and W. D. Smith, Bounds on determinants of perturbed diagonal matrices, *Linear Alg. Appl.* **466** (2015), 21–26.

[9] T. A. Brown and J. H. Spencer, Minimization of ± 1 matrices under line shifts, *Colloq. Math.* **23** (1971), 165–171. Erratum *ibid* pg. 177.

[10] P. Chebyshev, Des valeurs moyennes, *J. Math. Pure Appl.* **2** (1867), 177–184.

[11] G. F. Clements and B. Lindström, A sequence of (± 1)-determinants with large values, *Proc. Amer. Math. Soc.* **16** (1965), 548–550.

[12] R. W. Cottle, Manifestations of the Schur complement, *Linear Alg. Appl.* **8** (1974), 189–211.

[13] P. Erdős and J. Spencer, *Probabilistic Methods in Combinatorics*, Akadémiai Kiadó, Budapest, 1974. Also published by Academic Press, New York, 1974.

[14] N. Farmakis and S. Kounias, The excess of Hadamard matrices and optimal designs, *Discrete Math.* **67** (1987), 165–176.

[15] J. Hadamard, Résolution d'une question relative aux déterminants, *Bull. des Sci. Math.* **17** (1893), 240–246.

[16] D. Kessler and J. Schiff, *The asymptotics of factorials, binomial coefficients and Catalan numbers*, `http://u.math.biu.ac.il/~schiff/Papers/prepap3.pdf`, April 2006.

[17] C. Koukouvinos, M. Mitrouli and J. Seberry, Bounds on the maximum determinant for $(1, -1)$ matrices, *Bull. Inst. Combinatorics and its Applications* **29** (2000), 39–48.

[18] C. Koukouvinos, M. Mitrouli and J. Seberry, An algorithm to find formulæ and values of minors for Hadamard matrices, *Linear Alg. Appl.* **330** (2001), 129–147.

[19] W. de Launey and D. A. Levin, $(1, -1)$-matrices with near-extremal properties, *SIAM J. Discrete Math.* **23** (2009), 1422–1440.

[20] I. Livinskyi, *Asymptotic existence of Hadamard matrices*, M.Sc. thesis, University of Manitoba, `http://hdl.handle.net/1993/8915`, 2012.

[21] F. W. J. Olver, *Asymptotics and Special Functions*, Academic Press, New York, 1974.

[22] A. M. Ostrowski, Sur l'approximation du déterminant de Fredholm par les déterminants des systèmes d'equations linéaires, *Ark. Math. Stockholm* **26A** (1938), 1–15.

[23] T. Rokicki, I. Kazmenko, J-C. Meyrignac, W. P. Orrick, V. Trofimov and J. Wroblewski, *Large determinant binary matrices: results from Lars Backstrom's programming contest*, unpublished report, July 31, 2010.

[24] I. Schur, Über Potenzreihen, die im Innern des Einheitskreises beschränkt sind, *J. Reine Angew. Math.* **147** (1917), 205–232.

[25] F. Szöllősi, Exotic complex Hadamard matrices and their equivalence, *Cryptogr. Commun.* **2** (2010), 187–198.